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FATIGUE CRACK PROPAGATION RATE MEASUREMENTS IN RAIL STEELS 1. FULLY-HEAT-TREATED (OO & T) RAIL

D.Y. FEGREDO, O. VOSIKOVSKY and W. NEILL

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REPORT: MRP/PMRL 83-26 (TR)

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FATIGUE CRACK PROPAGATION RATE MEASUREMENTS IN RAIL STEELS

1. FULLY-HEAT-TREATED (OQ & T) RAIL

by

D.M. Fegredo, O. Vosikovsky and W. Neill

ABSTRACT

Fatigue crack propagation rates (da/dN) were measured, in preliminary experiments of a new rail steel project element, for two specimens from a fully heat treated (FHT), oil-quenched and tempered rail for stress intensity (ΔK) values between $\sim 14 \text{ MPa}\cdot\text{m}^{1/2}$ and $\sim 45 \text{ MPa}\cdot\text{m}^{1/2}$. Excellent reproducibility was obtained. A threshold stress intensity value was also determined on a third specimen. The crack propagation rates compare very well with those published for a similar FHT steel (threshold value not given). These results meet the experimental objective which was to ensure that the components machined for the type of compact tension specimen employed and the computer program designed to control the experiments on the MTS test machine are satisfactory.

LABORATOIRE DE RECHERCHE EN METALLURGIE PHYSIQUE
RAPPORT PRM/LRMP 83-26(TR)

TAUX DE CROISSANCE DE LA FISSURE DUE A LA FATIGUE EN ACIERS POUR RAILS
1. RAIL A TRAITEMENT THERMIQUE MAXIMAL (TTM) TREMPÉ EN HUILE ET REVENU

par

D.M. Fegredo, O. Vosikovsky and W. Neill

RÉSUMÉ

On a entrepris des essais préliminaires d'un élément nouveau employé dans un projet d'acier pour rails. Ces essais ont permis de mesurer les taux (da/dN) de croissance de la fissuration due à la fatigue de deux éprouvettes prises à un rail (TTM) trempé et revenu afin de calculer les valeurs (ΔK) de l'intensité des contraintes entre $\sim 14 \text{ MPa.m}^{1/2}$ et $\sim 45 \text{ MPa.m}^{1/2}$. On a obtenu une reproductibilité excellente. L'étude d'une troisième éprouvette a fourni une valeur de seuil de l'intensité des contraintes. Les taux de croissance de la fissure sont comparables à ceux fournis précédemment par un autre acier (TTM) semblable dont les valeurs de seuil ne figuraient pas dans la documentation. Ces résultats remplissent l'objectif de l'expérience qui était d'assurer que les pièces fabriquées pour l'analyse de cette espèce d'éprouvette à traction compacte seraient acceptables et que le programme d'ordinateur qui contrôle les expériences faites à la machine MTS serait adéquat.

INTRODUCTION

It is important to know the fatigue properties of rails because many service defects such as transverse fissures, shells and longitudinal defects (horizontal split head) are instigated by fatigue, i.e., caused by repeated wheel/rail contact stresses (1). They can lead to rail failures and derailments unless detected in time. In general, the stronger the steel the better its fatigue resistance although it has been stated that vacuum-treated rails are inferior to those more conventionally processed (2). However, Soviet work (3), cited by Stone and Steele (2), implies that maximum resistance to fatigue occurs at a hardness of 380 HB (Rc 41) for rail steels.

A number of studies have been carried out recently on the fatigue crack propagation threshold stress intensity values i.e., the value of ΔK below which crack propagation does not occur, and the fatigue crack propagation rates for higher stress intensity ranges of different steels. Thus, Marich (4) has determined the fatigue crack propagation rates of the following rail types: Standard, Cr-V, Cr-Mo-V and Russian through-hardened. These had hardnesses of 273 HB, 338 HB, 377 HB and 358 HB (Rc 28.5, Rc 36.5, Rc 40.5 and Rc 38.5) respectively. He concluded that cracks nucleate less easily in un-notched material as the tensile stress increases, and that materials with higher critical stress intensity (K_{IC}) factors generally exhibit lower fatigue crack growth rates. Other work (5) on standard C-Mn rails has determined threshold stress intensity values ΔK_{th} to vary approximately from 7 to 9 MPa m^{1/2}.

A comprehensive program of research on premium rail in CANMET addresses the question of developing an improved rail by processes that could be feasible in Canada's two rail mills. Work has been reported on the two approaches adopted:

- (i) the accelerated cooling of lean-alloy eutectoid steels following rolling (6) and
- (ii) the controlled cooling of premium alloy grades to produce very hard (>Rc 43) strong pearlitic structures (7).

Both approaches, particularly the latter, have the objective of producing wear-resistant rail. It is felt to be important to establish a facility in PMRL, CANMET, that can determine the fatigue properties of both the experimental steels developed and commercial rail steels and as a by-product also

roughly determine the fracture toughness critical stress intensity K_{IC} parameter.

The basic objectives of the preliminary experiments were to

- (i) test the new fatigue components (clevises and studs),
- (ii) determine the accuracy of the compliance technique in calculating crack length for the type of fatigue specimen used and;
- (iii) compare experimental results with those in the literature.

This report describes the types of fatigue specimens, linkages, machine and computer program used and discusses the preliminary results on three specimens.

EXPERIMENTAL METHODS

Compact tension (CT) specimens, clevis and pin dimensions conform to ASTM Designation E647-81 (8), and are shown in Fig. 1 (a,b). Because of machining difficulties the CT machined notch was substituted by a 3.5 mm long, 0.18 mm thick electric discharge machine (EDM) slit. The specimens were made from the top of the rail-head, Fig. 2.

The specimens were fatigue-tested on an electro-hydraulic computer-controlled MTS system by constant amplitude sinusoidal loads. An R (minimum load/maximum load) value of ~ 0.05 was generally used, and a clip gauge, attached between knife edges and mounted with adhesive onto the specimen, allowed compliance measurements to be made. Figure 3 shows a specimen in the MTS.

To eliminate the effect of the EDM slit, each specimen was precracked using a force range of 0.7 to 14 kN until the fatigue crack had extended 1.5 mm from the slit root. The specimens were then subjected to constant amplitude loading applied at a frequency of 20 Hz. Three computer programs are used to control the tests under consideration. The first one, INTRO, is used simply as documentation and for the input of testing parameters. The second program, COD, controls the test and the third, PLOT, outputs the data from the test in tabular and graphical forms. These programs are detailed in the Appendix.

The compliance technique is used to monitor crack length. Crack opening displacement (COD) is measured by the clip gauge and this allows crack length a to be calculated by the following equation (9):

$$a = (1.001 - 4.6695u + 18.46u^2 - 236.82u^3 + 1214.9u^4 - 2143.6u^5) \cdot W \quad \text{Eq 1}$$

where

$$u = \frac{1}{(BE_m)^{1/2} + 1}$$

and

B = specimen thickness in mm

W = specimen width

E = Young's Modulus (kN/mm²)

m = slope of COD (mm) vs load P (kN)

The crack length is continuously monitored by the program. Once the crack has grown by a specified growth increment (generally, from 0.3 to 0.5 mm), values of ΔP (load range), a (crack length), N (elapsed number of cycles), da/dN (crack growth rate) and ΔK (stress intensity factor) are output into a data file. Load adjustments, if desired, are also made at the end of these crack growth increments. Thus, print-outs at various intervals, or on command, record the corresponding values of a , N , da/dN , ΔK and P in kN. ΔK is obtained from the specimen dimensions as follows (9):

$$\Delta K = \frac{\Delta P}{B \cdot W^{1/2}} \frac{(2 + \alpha)}{(1 - \alpha)^{3/2}} (-5.6\alpha^4 + 14.72\alpha^3 - 13.32\alpha^2 + 4.64\alpha + 0.886) \quad \text{Eq 2}$$

where

$$\alpha = a/W$$

However, crack length was also measured at various intervals on both faces of the specimen by two (x8, x10) travelling microscopes which could be read to ± 0.01 mm. These values were taken as exact and used as standards to compare with and correct, if necessary, the computer-calculated values of a , ΔK and da/dN for any particular N .

Threshold stress intensity values ΔK_{th} were obtained by precracking and then by decreasing stress intensity values until no crack propagation was detected in 10^6 cycles.

EXPERIMENTAL RESULTS

Six compact tension specimens were machined from fully heat-treated (FHT) oil quenched and tempered (OQ & T) Bethlehem steel rail heads. The chemical analysis and tensile properties of the steel are given in Table 1 (10). Crack propagation rates and approximate K_{IC} values for specimens broken in fatigue were determined for two specimens, 1 and 2, and the threshold stress intensity range ΔK_{th} was obtained for specimen 3.

Crack propagation rate (da/dN) versus stress intensity range ΔK plots are given in Fig. 4 for all three specimens. In addition, Fig. 4 has plots taken from Marich's (4) Fig. 18 for standard and Russian through-hardened (OQ & T) rails. The through-hardened rail was the only one for which Marich could not describe growth rates from duplicate runs by a single line. The present results show excellent reproducibility. Stress intensity values at fracture, $K_{frac} \sim K_{IC}$, of $\sim 53 \text{ MPa.m}^{1/2}$ and $\sim 57 \text{ MPa.m}^{1/2}$ were obtained for specimens 1 and 2 respectively. A threshold stress intensity ΔK_{th} value of $16.8 \text{ MPa.m}^{1/2}$ was obtained for specimen 3. Figure 5 shows the fracture of specimen 1. The fatigue and final fracture areas are clearly delineated.

DISCUSSION

Two of the experimental objectives are to:

- (i) test the new machined fatigue components (clevises and studs) - no problems were encountered during the tests,
- (ii) determine the accuracy of the compliance technique in calculating crack length for the particular specimen dimensions and material used. The calculated values of crack length using Eq 1, in the computer print-out, were compared to visual observations. Good agreement was obtained. Differences between the two sets of values varied but were always $< 0.3 \text{ mm}$. The accuracy of the compliance method appears to be satisfactory.

The experiments on specimens 1 and 2 allowed the reproducibility of the crack propagation results to be checked. Figure 4 shows this to be excellent. Furthermore, crack propagation rates for varying ΔK correspond well with those obtained by Marich (4) on a similar type of premium rail (OQ & T). Unfortunately, Marich did not determine ΔK_{th} and the value of $\sim 17 \text{ MPa}\cdot\text{m}^{1/2}$ obtained on specimen 3 appears significantly higher than the values of $\sim 7-9 \text{ MPa}\cdot\text{m}^{1/2}$ reported by Fowler and Tetelman (5) on standard rails.

Two reasons may be advanced to explain this discrepancy:

- (1) It may be attributed to the significantly higher hardness and strength of FHT premium rails ($\sim R_c 38$, $Y_S \sim 810 \text{ MPa}$, $UTS \sim 1170 \text{ MPa}$) compared with standard rails ($\sim R_c 28$, $Y_S \sim 475 \text{ MPa}$, $UTS \sim 930 \text{ MPa}$). However, this postulate is weakened by the results of Gray et al. (10) which showed that coarsening the prior austenite grain size increases the threshold stress intensity level. Fully-heat-treated rails have a smaller austenite grain size than standard rails.
- (2) Alternately the heat-treatment of FHT rails includes an oil-quench which introduces residual transverse compressive stresses at the top of the rail-head (11). These peak at $\sim 200 \text{ MPa}$ at a depth of $\sim 3 \text{ mm}$ from the surface but are still high at 5 mm depth. The residual stresses then diminish to 0 MPa at a depth of $\sim 10 \text{ mm}$ and then gradually change sign. Residual stresses in the axial direction were not measured by Mitchell (11) but are approximately equal to the transverse stresses according to Melwin and Johnson (12). Since the present specimens were made from the top of the rail-head, Fig. 2, it is possible that the compressive residual stresses there increase ΔK_{th} . This postulate will be tested by machining and subjecting more specimens to fatigue from the lower part of the rail-head where tensile residual stresses exist.

The average of the two K_{frac} ($\sim K_{IC}$) values obtained is $55 \text{ MPa}\cdot\text{m}^{1/2}$. This agrees fairly well with the K_{IC} value of $48.5 \text{ MPa}\cdot\text{m}^{1/2}$ reported by Parsons (13) for a similar rail.

CONCLUSION

The computer-controlled MTS system in PMRL, CANMET, appears to generate valid fatigue crack propagation data on compact tension specimens of rail steels.

ACKNOWLEDGEMENTS

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Table 1. Chemical analysis and mechanical properties (at 24°C) of fully-heat-treated (OQ & T) rail steel.

C	Analysis wt %					Strength MPa		El %	RA %	Charpy (J)		$K_{IC_{1/2}}$ MPa.m ^{1/2}	Hardness R_C
	Mn	Si	S	P	Al	YS (0.2%)	UTS			Un- notched	V- notch		
0.72	0.93	0.19	0.04	0.012	0.015	814	1138	16	25	213	9.5	48.5	38

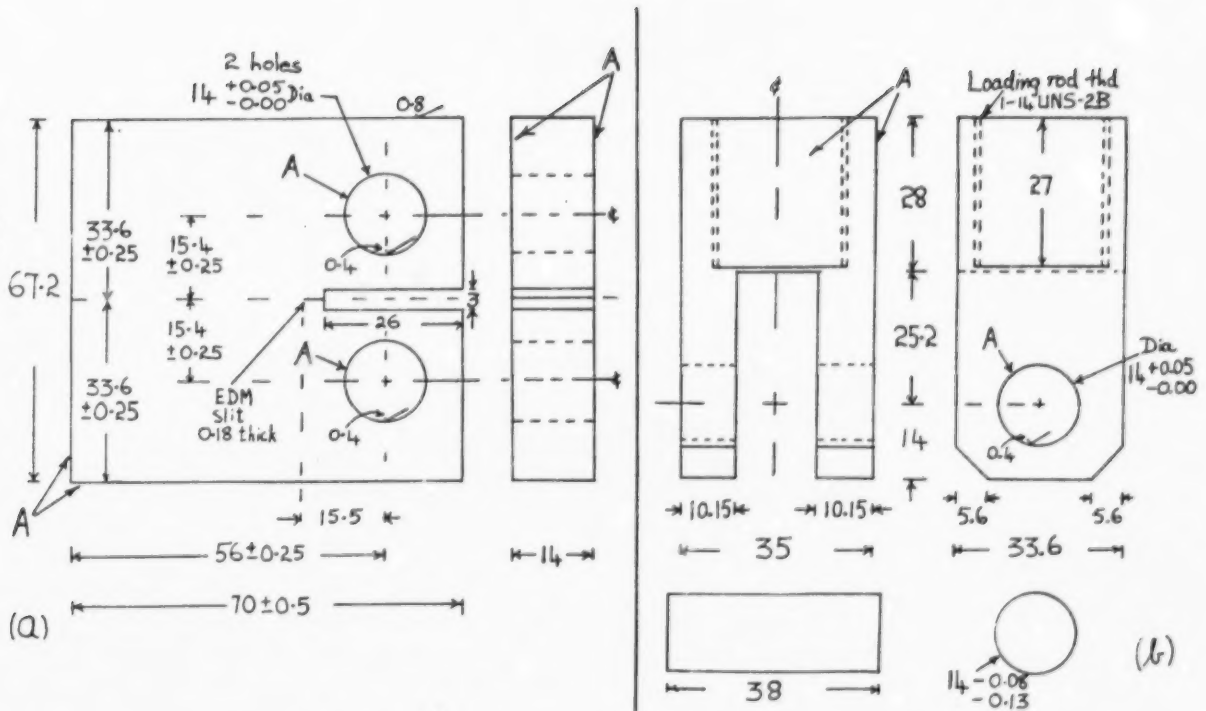


Fig. 1. Dimensions of (a) compact tension fatigue specimen and (b) clevis and pin (SPS 245 heat-treated to Rc 45).
 NOTE: Dimensions are in mm. A surfaces shall be perpendicular and parallel as applicable to within 0.11 mm. The intersection of the tips of the machined notch with the specimen faces shall be equally distant from the top and bottom edges of the specimen to within 0.03 mm.

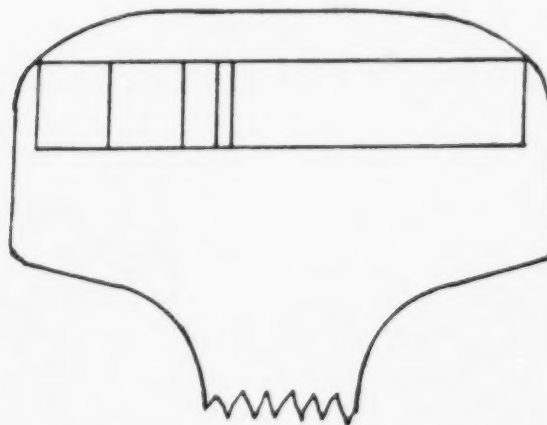


Fig. 2. Position of fatigue specimen in rail-head.

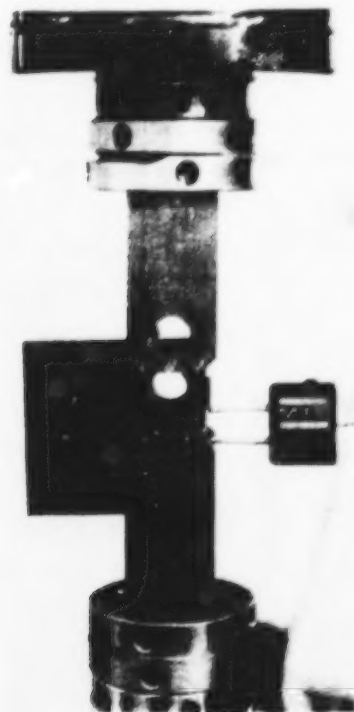


Fig. 3. Fatigue specimen in the MTS machine. Clip-gauge mounted between knife edges glued to the specimen. (neg 8079)

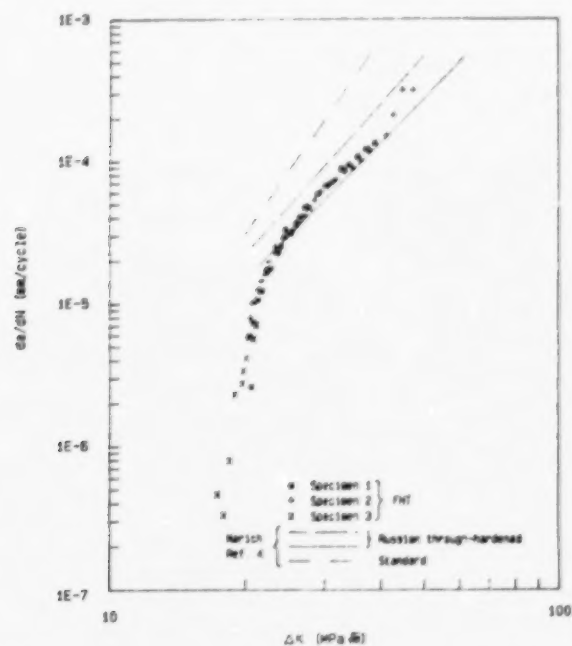


Fig. 4. Stress intensity factor range versus crack propagation rate data points for specimens 1 to 3. Curves from ref 4 (Marich) are also included. (neg 9530)



Fig. 5. Fracture surface of specimen 1. (neg 8080)

APPENDIX - Computer Programs INTROOC, COD and PLOTG

INTROOC

```
10 REM PART I - COMPUTER-CONTROLLED FATIGUE CRACK GROWTH RATE TEST
20 REM (USING THE CRACK OPENING DISPLACEMENT METHOD FOR
30 REM CALCULATION OF CRACK LENGTH)
40 REM
50 REM INTROOC - DOCUMENTATION (LIST OF VARIABLES) AND INPUT OF TESTING
60 REM PARAMETERS (SPECIMEN DIMENSIONS, LOAD RATIO, ETC.)
70 REM
80 COMMON B,W,R1,R2,F1,E7,R,N,O1$,M0,A9
90 REM
100 REM *** COD ***
110 REM
120 REM A - PRESENT CRACK LENGTH (MM)
130 REM A0 - CRACK LENGTH AT LAST LOAD-STEP
140 REM A7 - CRACK LENGTH TWO LOAD-STEPS AGO
150 REM A9 - INITIAL CRACK LENGTH
160 REM B - SPECIMEN THICKNESS (MM)
170 REM B1 - D(COD)/D(P)
180 REM B2 - INTERMEDIATE VALUE USED IN CALCULATING A
190 REM C - NORMALIZED K-GRADIENT
200 REM C1 - PERCENTAGE DECREASE IN LOAD
210 REM D - DA/DN
220 REM E1 - CORRECTION FOR YOUNG'S MODULUS
230 REM E2-6 - INTERMEDIATE VALUES USED TO FIND E7
240 REM E7 - YOUNG'S MODULUS
250 REM F - FREQUENCY (HERTZ)
260 REM F1 - FREQUENCY IN FUNCTION GENERATOR FORM
265 REM F2 - FLAG TO INDICATE THAT A PREMATURE LOAD-STEP IS DESIRED
270 REM F4 - FLAG TO INDICATE WHETHER THE TEST IS IN THE K-DECREASING
280 REM OR K-INCREASING PORTION
290 REM F5 - FLAG TO INDICATE THAT A LOAD-STEP HAS JUST TAKEN PLACE
300 REM THEREFORE IT IS TIME TO CALCULATE C
310 REM F6 - FLAG TO INDICATE THAT IT IS TIME FOR ANOTHER LOAD-STEP
320 REM F7 - FLAG TO INDICATE THAT LOAD WILL BE DECREASED UNTIL
330 REM DELTA K = THE VALUE SPECIFIED IN F7
340 REM F8 - FLAG TO INDICATE THAT ONE OR MORE VALUES OF DELTA K
350 REM HAVE BEEN CALCULATED
360 REM F9 - FLAG TO INDICATE THAT AUTO-CORRECTION OF YOUNG'S MODULUS
370 REM IS DESIRED AFTER EACH LOAD-STEP.
380 REM H(1) - MIN. LOAD READING DURING LAST DATA ACQUISITION
390 REM H0(1) - MIN. CLIP GAUGE READING FROM LAST DATA ACQUISITION
400 REM J - ELAPSED TIME COUNTER
410 REM K - DELTA K
420 REM K(1) - VALUE OF DELTA K ONE LOAD-STEP AGO
430 REM K(2) - VALUE OF DELTA K TWO LOAD-STEPS AGO
440 REM M - LOAD IN TERMS OF % OF RANGE
450 REM M0 - MAXIMUM NUMBER OF FUNCTION GENERATOR REPETITIONS (32767)
460 REM N - NUMBER OF CYCLES
470 REM N0 - NUMBER OF CYCLES AT LAST LOAD-STEP
480 REM N1 - NUMBER OF POINTS USED IN CALCULATING D(COD)/D(P)
490 REM P0 - DELTA P
500 REM Q(1) - MAX. LOAD FROM LAST DATA ACQUISITION
510 REM Q0(1) - MAX. CLIP GAUGE READING FROM LAST DATA ACQUISITION
520 REM R - LOAD RATIO
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530 REM R1 - CLIP GAUGE RANGE (MM)
540 REM R2 - LOAD CELL RANGE (KN)
550 REM S - ARRAY CONTAINING LOAD READINGS
560 REM T - 0 TOLERANCE FOR DA/DN
570 REM U - INTERMEDIATE VALUE USED IN CALCULATING A
580 REM V - FG CONTROL ARRAY
590 REM W - SPECIMEN WIDTH
600 REM X1 - NUMBER OF DATA ACQUISITIONS COMPLETED
610 REM Z1 - CRACK LENGTH INCREASE REQUIRED TO PERFORM A LOAD-STEP
620 REM Z2-Z5 - REGRESSION SUMS USED IN CALCULATING D(COD)/D(P)
630 REM
640 REM D1$ - FILE TO CONTAIN P,A,N,DA/DN, DELTA K DATA
650 REM
660 REM
670 REM *** PLOT ***
680 REM C4 - NUMBER OF HEADER LINES
690 REM H1,H2,H3,H4 - HIGHEST ENTRIES IN A,N,D AND K ARRAYS
700 REM L1,L2,L3,L4 - LOWEST ENTRIES IN A,N,D AND K ARRAYS
710 REM J - NUMBER OF DATA POINTS
720 REM U - PLOT TYPE INDICATOR
730 REM U1,U2 - LOWER AND UPPER X BOUNDS
740 REM U3,U4 - LOWER AND UPPER Y BOUNDS
750 REM U5,U6 - THE SPACING BETWEEN MARKS ON X AND Y AXES
760 REM V1$,V2$ - LABELS FOR GRAPHS
770 REM X1,X2 - MAX AND MIN X VALUES USED FOR GRAPHS
780 REM Y1,Y2 - MAX AND MIN Y VALUES USED FOR GRAPHS
790 REM
800 REM *** INTERRUPT ROUTINES FOR COD ***
810 REM
820 REM *C* - CHANGE % DECREASE/INCREASE IN LOAD OR CRACK INCREMENT
830 REM *F* - CHANGE CYCLING FREQUENCY
840 REM *H* - HOLD/HAUT TEST
850 REM *R* - CHANGE LOAD CELL OR CLIP GAUGE RANGE
860 REM *S* - PRINT STATUS REPORT
870 REM *Y* - CORRECT YOUNG'S MODULUS
880 REM
890 REM
900 REM OBTAIN INITIAL DATA
910 REM
920 PRINT "*** INITIAL DATA ***" \ PRINT
930 PRINT "PLEASE SPECIFY THE FOLLOWING" \ PRINT
940 PRINT "F=INITIAL FREQUENCY (HZ)*; \ INPUT F
950 PRINT "TESTING FREQUENCY*"; \ INPUT FO
960 PRINT "R=LOAD RATIO (P-MIN/P-MAX)*; \ INPUT R
970 PRINT "B=SPECIMEN THICKNESS (MM)*; \ INPUT B
980 PRINT "W=SPECIMEN WIDTH (MM)*; \ INPUT W
990 PRINT "A9=INITIAL CRACK LENGTH (MM)*; \ INPUT A9
1000 PRINT "N=NUMBER OF CYCLES ALREADY COMPLETED*"; \ INPUT N
1010 PRINT "R1=CLIP GAUGE RANGE (MM)*; \ INPUT R1
1020 PRINT "R2=LOAD CELL RANGE (KN)*; \ INPUT R2
1030 PRINT "E7=YOUNG'S MODULUS (MPA)*; \ INPUT E7
1040 PRINT "FILE TO CONTAIN THE RESULTS*"; \ INPUT D1$
1050 M0=32767
1060 F1=INT(F*4095/50)
1070 OPEN "HEADER" FOR OUTPUT AS FILE #1
1080 PRINT #1,"SPEC. NO. ="I" FREQUENCY ="FO"HZ LOAD RATIO ="R

```

1090 PRINT #1, "SPECIMEN THICKNESS ="B"MM SPECIMEN WIDTH ="W"MM"
1100 CLOSE
1110 CHAIN "COD"

COD

```
10 QUIT
20 TIME(10)
30 EDUMP
40 DIM K(2),H(1),Q(1),H0(1),Q0(1),S(500),Z(500),A8(6)
50 OPEN O1$ FOR OUTPUT AS FILE #1
60 OPEN "HEADER" FOR INPUT AS FILE #2
70 IF END #2 THEN 100
80 INPUT #2,Q$ \ PRINT #1,Q$
90 GO TO 70
100 CLOSE #2
110 KILL "HEADER"
120 PRINT #1,"@"
130 F5=1 \ F6=0 \ F7=0 \ F8=0 \ F9=0 \ A=A9 \ A0=A9 \ F4=-1
140 A$="DECREASE" \ B$="0"
150 BUTN("F", LINE 3200 ) \ BUTN("S", LINE 2800 ) \ BUTN("Y", LINE 2120 )
160 BUTN("C", LINE 3300 ) \ BUTN("H", LINE 3500 ) \ BUTN("R", LINE 3600 )
170 BUTN("I", LINE 2330 ) \ BUTN("P", LINE 3900 )
180 ENABL
190 PRINT \ PRINT "*** FATIGUE CRACK GROWTH RATE TEST ***" \ PRINT
200 PRINT "WHAT IS THE INITIAL LOAD (KN)";
210 INPUT M \ M=M/F2*100
220 PRINT "BY WHAT PERCENTAGE SHOULD LOAD BE 'A$'D EACH TIME";
230 INPUT C1
240 PRINT "WHAT IS THE CRACK INCREMENT"; \ INPUT Z1
250 T=1.00000E-07
260 PRINT "DO YOU WANT AUTO-CORRECTION OF YOUNG'S MODULUS AFTER EACH LOAD-STEP";
270 INPUT Q$ \ IF SEG$(Q$,1,1)="Y" THEN F3=1
280 PRINT \ PRINT "PRESS <CR> TO START TEST" \ PRINT
290 Q=SYS(4) \ IF Q<13 THEN 290
300 U(0)=0 \ U(1)=F1 \ U(2)=0 \ U(4)=M0 \ U(6)=0
310 U=7
320 GO TO 370
330 REM
340 REM ADJUST LOAD
350 M=M+F4*C1/100*M
360 F5=1
370 PRINT "LOAD NOW AT 'M'% OF RANGE ="M/100*R2"KN"
380 U(3)=INT(20.47*M*R) \ U(5)=INT(20.47*M) \ U(7)=U(3)
390 REM
400 REM SET FUNCTION GENERATOR AND ACQUIRE DATA
410 Q2=83000/F1
420 FG(1,U,M0,2,1)
430 IF X1=0 THEN ETIME \ SLEEP(15) \ PEND("Y")
440 ETIME(J) \ SLEEP(J+10)
450 GOSUB 3770
460 IF F9=0 THEN 480
470 IF F5=1 THEN GOSUB 2130
480 X1=X1+1
490 ETIME(J)
500 N=N+J*F1*50/4095
510 ETIME
520 REM
530 REM CALCULATE A
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```
540 GOSUB 2000
550 IF F4=1 THEN 620
560 REM
570 REM IF DA/DN<TOLERANCE THEN END LOAD-SHEDDING. OTHERWISE, CALCULATE
580 REM DELTA K.
590 IF F8<3 THEN 620
600 IF D<T THEN 970
610 IF N-N0>1.00000E+06 THEN IF (A-A0)/(N-N0)<T THEN 970
620 P0=(Q(1)-H(1))/2047*R2
630 IF Q(1)-H(1)<=(V(5)-V(3))/2 THEN GOSUB 3500
640 E4=A/W
650 K1=(((-5.6*E4+14.72)*E4-13.32)*E4+4.64)*E4+.886
660 K=P0/(B*SQR(W))*(2+E4)/(1-E4)^1.5*K1*SQR(1000)
670 IF INT(X1/100)=X1/100 THEN FEND('S')
680 IF F5=0 THEN 740
690 F5=0
700 ON F8+1 GO TO 720,710,730
710 K(2)=K(1) \ K(1)=K \ F8=2 \ GO TO 740
720 K(1)=K \ F8=1 \ GO TO 740
730 C=1/K(1)*(K-K(2))/(A-A7) \ K(2)=K(1) \ K(1)=K
740 IF F7=0 THEN 760
750 IF K<=F7 THEN PRINT 'DELTA K='K \ GOSUB 2330
760 REM
770 REM IF THE CRACK HAS GROWN 'Z1' MM SINCE THE LAST LOAD-STEP
780 REM THEN CALCULATE THE NORMALIZED K-GRADIENT AND ADJUST LOAD
790 IF F2=1 THEN 820
800 IF N-N0<2500 THEN 940
810 IF A-A0<Z1 THEN F6=0 \ GO TO 940
820 F6=F6+1
830 AB(F6)=A
840 IF F6<3 THEN 940
850 GOSUB 2700
860 D=(A-A0)/(N-N0)
870 PRINT
880 PRINT #1,P0,'A','N','D','(K(1)+K)/2 \ PRINT #1,B \ PRINT '*****'
890 PRINT 'DELTA P='P0 \ PRINT 'A='A \ PRINT 'N='N \ PRINT 'DA/DN='D
900 PRINT 'DELTA K='(K(1)+K)/2 \ PRINT '*****'
910 PRINT \ N0=N \ A7=A0 \ A0=A \ F6=0 \ F2=0 \ A6=A0
920 IF A>=.5*W THEN GOSUB 3500
930 GO TO 350
940 IF V(5)>2 THEN 410
950 PRINT 'DELTA K TH COULD NOT BE OBTAINED WITHIN SPECIFIED ACCURACY'
960 PRINT 'DA/DN='D \ PRINT
970 PRINT 'THRESHOLD STRESS INTENSITY OCCURS AT'M/100*R2*KN'
980 REM
990 REM PRINT OUT DELTA K TH AND START K-INCREASING TEST
1000 PRINT 'DELTA K TH='K
1010 GOSUB 2400
1020 GO TO 330
2000 REM
2010 REM SUBROUTINE TO CALCULATE A
2020 REM CALCULATE SLOPE OF COD VS. LOAD
2030 GOSUB 2900
2040 B2=B1*E7*B*R1/R2/1000
2050 U=1/(SQR(B2)+1)
2060 A=W*((( (-2143.6*U+1214.9)*U-236.82)*U+18.46)*U-4.6695)*U+1.001)
```

```
2070 RETURN
2120 REM
2122 REM CORRECTION OF YOUNG'S MODULUS
2125 PRINT "WHAT IS THE MEASURED CRACK LENGTH"; \ INPUT A6
2130 REM ACQUIRE CRACK OPENING DISPLACEMENT AND LOAD DATA
2140 ETIME(J) \ ETIME
2150 N=N+J*F1*50/4095
2160 GOSUB 3770
2170 REM
2180 REM CALCULATE SLOPE OF COD VS. LOAD
2190 GOSUB 2900
2200 REM
2210 REM CALCULATE THE CORRECTED VALUE FOR YOUNG'S MODULUS
2240 E4=A6/W \ E2=1+.25/E4 \ E3=((1+E4)/(1-E4))^2
2250 E5=((((-14.494*E4+35.05)*E4-16.61)*E4-14.231)*E4+12.678)*E4+1.6137
2260 E6=E2*E3*E5
2270 E1=1/(B1*R1/R2*B)
2280 E7=E6*E1*1000
2290 PRINT \ PRINT "SPECIFIC VALUE OF YOUNG'S MODULUS IS"E7
2300 RETURN
2330 PRINT \ PRINT "YOU NOW HAVE THREE OPTIONS:"
2340 PRINT "      1) START K-INCREASING TEST WITH INITIAL P MAX ="M"% OF RANGE"
2350 PRINT "      2) DECREASE LOAD UNTIL DELTA K = A SPECIFIED VALUE"
2360 PRINT "      3) DECREASE LOAD UNTIL DELTA K TH IS REACHED"
2370 PRINT \ PRINT "YOUR CHOICE"; \ INPUT Q
2375 A$="DECREASE" \ F4=-1 \ B$="-"
2380 ON Q GO TO 2400,2410,2430
2390 GO TO 2340
2400 PRINT \ PRINT "COMMENCING K-INCREASING TEST"
2405 A$="INCREASE" \ F4=1 \ B$="+"
2407 RETURN
2410 PRINT \ PRINT "DECREASE LOAD UNTIL DELTA K =(MPA M^1.5)"; \ INPUT F7
2420 RETURN
2430 PRINT \ PRINT "LOAD SHEDDING WILL CONTINUE UNTIL DA/DN="T
2440 RETURN
2700 REM
2710 FOR C8=1 TO 2
2720 FOR C9=1 TO 2
2730 IF A8(C9)/=A8(C9+1) THEN 2750
2740 A8(6)=A8(C9) \ A8(C9)=A8(C9+1) \ A8(C9+1)=A8(6)
2750 NEXT C9
2760 NEXT C8
2770 A=A8(2)
2780 RETURN
2800 REM
2810 REM INTERRUPT ROUTINE "S" - PRINT STATUS REPORT
2820 PRINT \ PRINT "A="A \ PRINT "N="INT(N) \ PRINT "DELTA K="K
2830 PRINT "DA/DN="(A-A0)/(N-N0) \ PRINT "C="C
2840 PRINT "LOAD ="M"% OF RANGE ="M/100*R2"KN"
2850 PRINT "LOAD-"A$" WILL OCCUR AT A="A0+Z1" MM"
2860 RETURN
2900 REM
2910 REM SUBROUTINE TO CALCULATE SLOPE OF CRACK OPENING VS. LOAD
2920 REM
2930 REM FIND RANGE OF VALID POINTS AND CALCULATE REGRESSION SUMS
2940 N1=0 \ Z5=0 \ Z2=0 \ Z3=0 \ Z4=0
```

```
2950 D1=Q(1)-H(1) \ T1=Q(1)-D1*.7
2960 DSABL
2970 FOR I=2 TO 500
2980 IF S(I)>S(I-1) THEN 3050
2990 IF S(I)<T1 THEN 3050
3000 N1=N1+1
3010 Z5=Z5+Z(I)*S(I)
3020 Z2=Z2+S(I)
3030 Z3=Z3+Z(I)
3040 Z4=Z4+S(I)^2
3050 NEXT I
3060 REM
3070 REM CALCULATE SLOPE
3080 B1=(Z5-Z2*Z3/N1)/(Z4-Z2^2/N1)
3090 RETURN
3200 REM
3210 REM INTERRUPT ROUTINE "F" - CHANGE LOADING FREQUENCY
3220 PRINT
3230 PRINT "FREQUENCY IS NOW SET AT "V(1)*50/4095"HZ"
3240 PRINT "NEW FREQUENCY"; \ INPUT F
3245 F1=INT(F*B1.9)
3250 V(1)=F1
3260 RETURN
3300 REM
3310 REM INTERRUPT ROUTINE "C" - CHANGE LOAD-STEP/CRACK INCREMENT
3320 PRINT
3330 PRINT "CHANGE 1) % LOAD "A$
3340 PRINT " 2) CRACK INCREMENT" \ PRINT "YOUR CHOICE"; \ INPUT Q
3350 ON Q GO TO 3380,3400
3370 GO TO 3330
3380 PRINT "PRESENT "A$" IS "C1 \ PRINT "NEW "A$; \ INPUT C1
3390 GO TO 3410
3400 PRINT "PRESENT INCREMENT IS "Z1 \ PRINT "NEW INCREMENT"; \ INPUT Z1
3410 RETURN
3500 REM
3510 REM INTERRUPT ROUTINE "H" - HOLD/END TEST
3520 ETIME(J) \ N=N+J*F1*50/4095
3530 X=V(5) \ V(5)=V(3)
3540 PRINT \ PRINT "END TEST"; \ INPUT Q$
3550 IF SEG$(Q$,1,1)="Y" THEN 4000
3560 PRINT "CYCLING RESUMED"
3570 V(5)=X \ ETIME
3575 EDUMP
3580 RETURN
3600 REM
3603 REM INTERRUPT ROUTINE "R" - CHANGE LOAD CELL/CLIP GAUGE RANGE
3607 PRINT "CHANGE: 1) LOAD CELL RANGE"
3610 PRINT " 2) CLIP GAUGE RANGE" \ PRINT "YOUR CHOICE"; \ INPUT Q
3620 F6=0
3630 IF Q=2 THEN 3740
3640 Y1=V(3) \ Y2=V(5)
3650 V(5)=0 \ V(3)=0
3660 ETIME(J) \ N=N+J*F1*50/4095
3670 PRINT "NEW LOAD CELL RANGE"; \ INPUT Y3
3680 PRINT "TURN OFF HYDRAULICS, RESET RANGE, PRESS <CR> TO RESTART"
3690 Q=SYS(4) \ IF Q<>13 THEN 3670
```

```
3700 M=M*R2/Y3 \ V(3)=INT(Y1*R2/Y3) \ V(5)=INT(Y2*R2/Y3) \ V(7)=V(3)
3710 R2=Y3
3720 ETIME
3730 RETURN
3740 PRINT "NEW CLIP GAUGE RANGE"; \ INPUT R1
3750 PRINT "TYPE <CR> TO RESUME" \ Q=SYS(4)
3760 RETURN
3770 REM
3780 REM ACQUIRE DATA
3790 H=0 \ Q=0 \ S=0 \ Z=0 \ Q0=0 \ H0=0
3791 QUIT \ DACQ(4,Q,0,Q2) \ DACQ(5,H,0,Q2) \ DACQ(4,Q0,1,Q2)
3792 DACQ(5,H0,1,Q2) \ DACQ(3,S,0,1) \ DACQ(6,Z,1,1)
3800 DSABL \ RESET \ START
3810 IF S<500 THEN 3810
3820 IF Q=0 THEN 3820
3830 IF H=0 THEN 3830
3840 IF Q0=0 THEN 3840
3850 IF H0=0 THEN 3850
3860 HOLD \ ENABL
3870 RETURN
3900 F2=1
3910 RETURN
4000 PRINT "N ="N
4010 END
```

PLOTG

```
10 REM PART III - COMPUTER-CONTROLLED FATIGUE CRACK GROWTH RATE TEST
20 REM
30 REM PLOT - PLOTTING OF TEST DATA
40 REM
50 DIM A(400),N(400),P(400),D(400),K(400),A$(400)
60 PRINT \ PRINT "*** PLOTTING OF TEST DATA ***" \ PRINT
70 PRINT \ PRINT "FILE NAME"; \ INPUT O1$
80 REM
90 REM INPUT DATA FROM PART II
100 REM
110 OPEN O1$ FOR INPUT AS FILE #1
120 PRINT "LINE UP PAPER AND PRESS <RETURN>"
130 Q=SYS(4) \ IF Q<>13 THEN 130
140 C4=0
150 C4=C4+1 \ INPUT #1,H$(C4)
160 IF H$(C4)<>"0" THEN PRINT H$(C4) \ GO TO 150
170 PRINT \ PRINT \ PRINT
180 J=0 \ PRINT " DELTA P", " " "CHR$(97)" " " " " "N", " " "CHR$(100)CHR$(97)"/
"CHR$(100)"N", " DELTA K"
190 PRINT " -----", " -----", " -----", " -----", " -----"
200 PRINT
210 IF END #1 THEN 250
220 J=J+1
230 INPUT #1,P(J),A(J),N(J),D(J),K(J),A$(J)
235 PRINT P(J),A(J),N(J),D(J),K(J);TAB(68)A$(J)
240 GO TO 210
250 CLOSE
260 REM
270 REM FIND HIGHEST AND LOWEST ENTRIES IN EACH ARRAY TO ALLOW PROPER
280 REM SCALING OF GRAPHS
290 REM
300 L1=A(1) \ H1=A(1) \ L2=N(1) \ H2=N(1) \ L3=D(1) \ H3=D(1)
310 L4=K(1) \ H4=K(1)
320 FOR C=2 TO J
330 IF A(C)>H1 THEN H1=A(C)
340 IF A(C)<L1 THEN L1=A(C)
350 IF N(C)>H2 THEN H2=N(C)
360 IF N(C)<L2 THEN L2=N(C)
370 IF D(C)>H3 THEN H3=D(C)
380 IF D(C)<L3 THEN L3=D(C)
390 IF K(C)>H4 THEN H4=K(C)
400 IF K(C)<L4 THEN L4=K(C)
410 NEXT C
420 REM
430 REM IF DESIRED, A GRAPH OF A VS. N IS PLOTTED
440 REM
445 PRINT \ PRINT \ PRINT
450 PRINT "DO YOU WANT A GRAPH OF A VS. N PLOTTED"; \ INPUT Q$
460 IF SEG$(Q$,1,1)="N" THEN 630
470 IF SEG$(Q$,1,1)="Y" THEN 500
480 PRINT "ENTER YES OR NO PLEASE"
490 GO TO 450
500 V1$="N (CYCLES)" \ V2$="A (MM)"
```

```
510 X1=L2 \ X2=H2
520 Y1=L1 \ Y2=H1
530 U=0
540 U2=(INT(X2/10^(INT(LOG10(X2))))+1)*10^(INT(LOG10(X2)))
550 U1=0
560 U3=5*INT(Y1/5)
570 U4=5*(1+INT(Y2/5))
580 U5=U2/5
590 U6=5
600 GOSUB 1000
610 FOR C=1 TO J \ MARK(A$(C),N(C),A(C)) \ NEXT C
620 GOSUB 1300
630 REM
640 REM IF DESIRED, A GRAPH OF DA/DN VS DELTA K IS PLOTTED
650 REM
660 PRINT "DO YOU WANT DA/DN VS DELTA K PLOTTED?"; \ INPUT Q$
670 IF SEG$(Q$,1,1)="N" THEN STOP
680 IF SEG$(Q$,1,1)="Y" THEN 700
690 PRINT "ANSWER YES OR NO PLEASE" \ GO TO 660
700 V1$="DELTA K (MPA M-5)" \ V2$="DA/DN (MM/CYCLE)"
710 X1=L4 \ X2=H4
720 Y1=L3 \ Y2=H3
730 U=3
740 U1=10^(INT(LOG10(X1)))
750 U2=10^(1+INT(LOG10(X2)))
760 U3=10^(INT(LOG10(Y1)))
770 U4=10^(1+INT(LOG10(Y2)))
780 U5=1
790 U6=1
800 GOSUB 1000
810 FOR C=1 TO J \ MARK(A$(C),K(C),D(C)) \ NEXT C
820 GOSUB 1300
830 GO TO 1500
1000 REM
1010 REM PLOT SUBROUTINE - PREPARES A GRAPH
1020 REM
1030 REM ACCESS GRAPHICS
1040 REM
1050 ASGR(Q) \ IF Q=0 THEN 1050
1060 ERASE
1070 REM
1080 REM PREPARE PLOTTING AREA
1090 REM
1100 PHYL(100,975,55,750)
1110 SCALE(U,U1,U2,U3,U4)
1120 REM
1130 REM PRINT AXES
1140 REM
1150 AXES(U1,U3)
1160 LABEL(V1$,V2$,U5,U6,1)
1170 RETURN
1300 REM
1310 REM SUBROUTINE TO GET HARD COPY AND RELEASE GRAPHICS
1320 REM
1330 COPY
1335 A=SYS(4)
```

1340 HOME \ ERASE \ DSGR
1350 RETURN
1500 END

POOR

QUALITY

ORIGINAL